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INTERDISCIPLINARY MODELS AND OPTIMIZATION TECHNIQUES USED IN WATER RESOURCES PLANNING*

by

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ABSTRACT

Along with the engineering judgment (based on the practical experiences) it is also essential to define quantitatively the interrelationships of the decision parameters in order to design and manage the water systems on a rational basis. Mathematical formulation of these systems and solutions of these models form a major part of such modeling effort. This report (which is prepared as a preliminary task on the D.O.A. Project Study of the Kissimmee River and Lake Okeechobee) is designed to serve as an introduction to the major multidisciplinary models and optimization techniques that are widely used in water resources planning. At the outset, various pathways of model building procedures are outlined. Then associated ecological, economic, social, political, technological and environmental models are described in a quantitative manner whenever possible. The general methodology of formulating these mathematical models along with the useful mathematical programming technqiues to arrive at the optimum values of the system variables is discussed. In light of these different kinds of models and varieties of optimization techniques, the past, present, and proposed modeling efforts for the Kissimmee River and Lake Okeechobee system are briefly reported. Adequacy of these efforts is discussed in relation to the data base, available computational capacity, validity of simplifications and verification procedure. Considering the possible points and counter points, statistical models in the form of time series analysis, multivariate analysis and advanced stepwise multiple regression analysis are suggested for these water systems to provide the management and operational information on an interim basis. Accordingly, some of the on-going programs of the FCD are structured to develop these quantitative models using the suggested advanced data processing techniques.

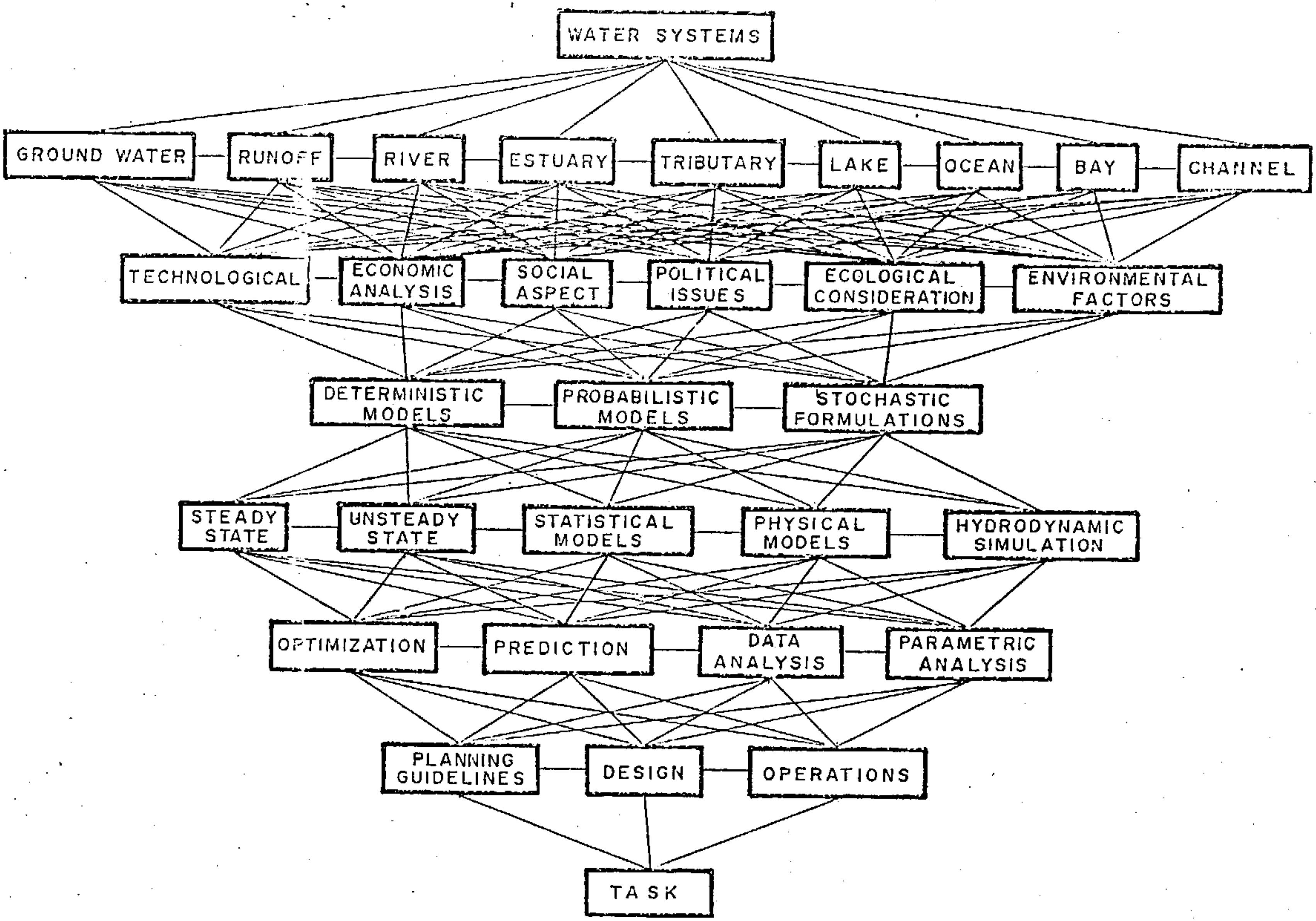
INTRODUCTION:

As a part of a water planning task every regional agency is invariably interested in broadening the understanding of the possible interactions between system variables associated with the broad category of water systems. Such interrelations, if based on sound scientific framework, can be instrumental in

1. establishing the useful cause-effect characteristics of the system,
2. assessing the behavior pattern of the particular phenomenon in question,
3. developing the computerized simulation procedures for detailed systems analysis, and
4. setting the rational planning guidelines.

The methodology of formulating quantitative expressions relating to system variables is traditionally known as model building procedure which can vary considerably as depicted in Figure 1. As can be seen from the generalized flow chart of Figure 1, there are numerous ways of evaluating the water systems of various kinds. The first level relates to the type of water system. In the second stage, the appropriate factors affecting the particular water system are considered; the third stage decides the right type of mathematical function; the next step relates to the analytical techniques involved in the analysis; at the fifth level, a specific goal is reflected whereas in the final stage the results of previous steps are used in completing the required task in question. It is to be noted here that the component parts of the Figure 1 are connected within and between the tiers. With such a representation of multilevel system characteristics, it is possible to

1. include all the viable pathways in the system evaluation schemes,
2. incorporate all the possible techniques to analyze the system performance,
3. add the newly developed concepts associated with water systems,
4. conceptually visualize the complexities with the overall methodology in general, and quantify certain factors in particular,



FLOW CHART OF THE POSSIBLE MODEL BUILDING PATHWAYS

FIGURE I

5. provide enough room for the practical judgment based on the sound professional experience and
6. finally choose a particular pathway for a specific location under various constraints.

In light of various pathways depicted in Figure 1, this report attempts to

1. discuss the various interdisciplinary models associated with the water systems,
2. describe various optimization techniques,
3. present the currently available and proposed modeling approaches for the Kissimmee River and Lake Okeechobee systems and finally,
4. foresee the adequacy of these modeling efforts for the Kissimmee River and Lake Okeechobee and suggest the modifications (if any) accordingly.

STATE-OF-THE-ART OF MODELING THE WATER SYSTEMS:

General

In an effort to represent the various interactions in water system by appropriate mathematical relationships, many types of interdisciplinary concepts and models were recently developed. For examples, Ecologists tried to understand the basic food and predator interconnections of the ecosystem, Engineers concentrated their efforts in formulating physical, chemical and biological water quality interactions, Hydrologists are interested in developing the techniques to estimate the quantity of water coupled with hydrodynamic properties of the water systems, Synecologist (systems ecologist) progressed the improvement of computer techniques for analysis of communities of organisms in water bodies and other habitats (14), Sociologists, Economists and Political Scientists discussed in detail the various implications of planning policies concerning the allocation of water resources. As a result of such healthy interdisciplinary efforts, many ecological, economic, water quality, hydrologic, hydraulic, social and political models are available. Since these models are develope independently and since these models need to be modified in many respects, the important task of tieing such pieces together is prerequiite for designing effective water planning guidelines. This, in turn, demands the adequate understanding of the concepts associated with these isolated pieces (in our case, mathematical models of various kinds). Therefore, in the following section an attempt is made to discuss these models briefly in light of some reported examples.

Ecological Models:

The basic objectives of ecological models are

1. to formulate ecological tactics manifested by specific biological species (in our case, aquatic biota).
2. to account for the pools of energy and nutrient interactions in aquatic ecosystem, and
3. to include these developed relationships in computerized simulation methodology.

With such general objectives, ecological models are so far developed through three perspectives. The first approach explores the cause and effect relationships within the individual ecological processes with the ultimate goal of simulation of population and ecosystem consequences. On the other hand, the second approach analyzes the ecosystems in light of energy and nutrient considerations and attempts to develop transfer functions between different ecological processes. Although many efforts were initially made to understand ecological processes only in a qualitative manner, recently major contributions of putting the ecological interrelationships in the mathematical forms are reported. For example, C. S. Holling tried to develop the ecological model for the biomass change in a grassland ecosystem. In such efforts a grassland ecosystem is first divided into six compartments and then following forcing function with system equations are obtained (21).

$$\tilde{V}_1(t) = \frac{3.0 + \cos\{3.1 + 2.0\,\frac{\pi(t-10)}{365}\}\,8.6}{1.4} \quad \text{(forcing function)}$$

$$\frac{\Delta V_2}{\Delta t} = 1.0V_1 + 0.004V_3 - \{0.0027\, e^{0.012t} + [0.002 + 0.002\,\mathrm{Sin}(2t-0.7)\ 1.4] + 0.0014\}V_2$$

$$\frac{\Delta V_3}{\Delta t} = 0.004V_2 - \{[0.0005 + 0.01\ \mathrm{Sin}(t+2)]\ 1.1^{(\frac{365-t}{110})} + 0.004\}V_3$$

$$\frac{\Delta V_4}{\Delta t} = 0.002V_2 - 0.001V_4$$

$$\frac{\Delta V_5}{\Delta t} = 0.00185[1.0 + \mathrm{Sin}(2t-1.56)]\ V_4 - 0.002V_5$$

$$\frac{\Delta V_6}{\Delta t} = \frac{0.00185\ [1.0 + \mathrm{Sin}(2t-1.56)]\ V_4 - 180.0 + V_5}{V_5} + 0.0014V_2 + 0.0007V_3$$

where

V_1 = photosynthetic input,

V_2 = live vegetation foliage,

V_3 = live vegetation roots,

V_4 = standing dead vegetation,

V_5 = litter,

V_6 = respiration,

t = time,

Mathematically, these equations are developed by fitting a suitable curve to the collected data. Therefore, these equations are well fitted only to the current data and for assumed compartmental structure of the ecosystem. The usefulness of these models to any other situation is generally not investigated.

Another approach for developing ecological models is to view population dynamics as birth and death processes and then to represent these processes in terms of either deterministic differential equations or probabilistic difference-differential equations. If the biological species involved in the ecosystem follow the logistic population growth, their population size at any time t is given by the following simple deterministic equation (42).

$$N_t = \frac{a}{b\ [1 + e^{-a(t-t_0)}]}$$

where

a, b, t_o are constants and are determined from the experimental data. If there exist Host-Parasite populations (predator-prey relationships) then one can start with the following pair of equations of Lotka and Volterra (41),

$$\frac{dH}{dt} = (a_1 - b_1P)H \qquad \text{and}$$

$$\frac{dp}{dt} = (-a_2 + b_2H)P$$

where H = number of Host species and P = number of Parasite species. Combining these two equations and with integration, we get finally,

$$a_2 \ln H - b_2H + a_1 \ln P - b_1P = \text{constant}.$$

This final solution represents a series of elliptical interrelationships between Host (H) and Parasite(P) with different values of constants a_1, a_2, b_1 and b_2. In contrast to the above deterministic approach, probabilistic formulation of a pure birth process gives the following expression in terms of the probability numbers. The probability that there will be the size of population "N" at time t

$$= P_N(t) = N-1\ C_{i-1}\ e^{-\lambda it}\ (1-e^{-\lambda t})^{N-1}$$

where

$$N-1C_{i-1} = \frac{N-1!}{N!i!}$$

N = population size,

i = initial population,

λ = birth rate,

t = time.

Similarly, mathematical models are developed for pure decay processes, combined birth-and death processes and spatial patterns of one, two and more species (42).

Such models are useful

1. in estimating the changes in certain species as a result of man made effects on the population of other predator-prey species,
2. in predictive analysis of the most likely and unlikely population sizes, and
3. in determining the diversity index which, in turn, reflect the ecological impact (beneficial and harmful) of existing or new planning policies.

This approach also requires an adequate amount of data to estimate the coefficients and then to verify the formulation from either the same set of data or from dther data collected under similar conditions. When compared with the first approach, it seems that the second approach can handle more effectively the complexities of the ecosystem.

The third approach considers the ecological interactions in light of energy requirements. This approach is extensively used by Odum in evaluating many ecological pathways (40). To start with, this approach identifies the network of the ecosystem and energy sources and sinks of the different ecological units. Based on these interrelationships, a dynamic analog computer with amplifiers is constructed to operate on different types of inputs. With different inputs, the flexibility of the overall ecological model is evaluated with reference to the environmental impact and energy factors. Although this approach is capable of handling the great amounts of ecological details, it indeed requires subjective judgment in choosing the activity coefficients in different pathways. In other words, this black box approach with complex networks may overlook the effects of some arbitrarily chosen key coefficients on the final outcome. However, considering the current inadequate understanding of ecological processes it can be argued that such analog modeling of complex ecological systems may be the only way to handle these complex ecological systems scientifically.

Thus, based on the above discussion of ecological models, it can be said that, although initial developments of ecological models were of qualitative type, there is increasing trend of developing quantitative models of complex interactions of the ecosystem. As a result, some refined quantitative ecological models are available which, in turn, can be built into the overall modeling procedure for the water system.

Economic Models:

Since the final goal of water resources planning is to set appropriate guidelines based on the systems evaluation of different viable alternatives, economic analysis of water systems is carried out to examine

1. the counteracting economic phenomenon associated with the particular water system,
2. the functional relationwhips between these phenomenon and finally
3. economic feasibility in terms of net benefits.

Although the objectives mentioned above seem straightforward, the methodologies used by economists and engineers seem to vary significantly. Economists,being social scientists, emphasize the conceptual understanding of complex economic interactions such as marginal supply and demand schemes, competitive and uncompetitive market system, national economic efficiency, income distribution, external diseconomies, economic production function, loss function, bargaining function, pricing modes, capital cost, operating and maintenance cost with discount factor, opportunity costs, financing, uncertainity with risk and reliability concepts, etc. etc. (34). Engineers, on the other hand, try to formulate the objective function with the required technological, economic, social, political objectives subjected to the various corresponding constraints. Such a formulation is then mathematically solved by various programming techniques to obtain optimum values of systems variables as described later in this report.

In other words, it appears that the economists develop models to explain the behavior of the economic components of the subsystem whereas engineers search for the optimum values of the system variables taking into account economics of the whole system. Since the formulation of economic behavior of subsystem is essential for the engineering optimization of the whole water system, recently many joint efforts are reported to develop economic models in the areas of

1. agricultural development,
2. surface water management,
3. regional water quality management,
4. groundwater management and,
5. salinity management in irrigation (23)

To illustrate the formulation of such economic models, two examples in the areas of water pricing and cost optimization in process design are presented in the following section.

When a regional agency is confronted with the problem of allocating water quantities to the three different users (municipal, industrial and agricultural) from four different sources (say, river, reservoir, groundwater and reclaimed wastewater), then an economic model of a deterministic type can be formulated to minimize the overall cost of water allocation. As a first step, the demand curves for municipal, industrial and agricultural uses are developed in terms of economic factors such as market value of a dwelling unit and water pricing. As suggested by Howe, such relationships take the following forms, (23)

$q = 206 + 3.47V - 1.30\ P_m$ (Municipal demand curve)

$q = 3657R_s^{0.309}\ P_m^{-0.930}$ (Summer sprinkling use)

$q = 87.29 - 1.54\ P_a$ (Agricultural demand curve)

$q = 21.0 - 0.175\ P_i$ (INdustrial demand curve)

where

$\bar{q}$ = total water demand in a particular category per unit time,

V = market value of the dwelling unit in thousands of dollars,

P_m= water pricing for municipal user in cents per thousand gallons,

P_a= water pricing for agricultural user in cents per thousand gallons,

P_i= water pricing for industrial user in cents per thousand gallons,

R_s= quantity which is a function of irrigable area in acres, average summer potential evapotranspiration and precipitation in inches.

Now using the following notations:

the quantities of water from source No. 1 to Municipal use as q_{11},
" " " " " " " 2 " " " " q_{21},
" " " " " " " 3 " " " " q_{31},
" " " " " " " 1 " Industrial use as q_{12},
" " " " " " " 2 " " " " q_{22},
" " " " " " " 3 " " " " q_{32},
" " " " " " " 1 " Agricultural use as q_{13},
" " " " " " " 2 " " " " q_{23}
" " " " " " " 3 " " " " q_{33}

and total amount of water drawn from source 1 = Q_1
" " " " " " " 2 = Q_2
" " " " " " " 3 = Q_3

cost of supplying q_{11} quantities of water = C_{11}
" " " " " " " = C_{21}
" " " " " " " = C_{31}, etc. etc.

water charge for municipal water = P_m
" " " " " = P_i
" " " " " = P_a

we can form an objective function (which considers the net profit to the regional water management agency) as

Net Profit = Return amount - cost of supplying water. Using the above notations and applying them to municipal, industrial and agricultural water, we get objective function as

$$\text{Net Profit} = P = P_m(q_{11} + q_{21} + q_{31}) - C_{11}q_{11} - C_{21}q_{21} - C_{31}q_{31}$$
$$+ P_i(q_{12} + q_{22} + q_{32}) - C_{12}q_{12} - C_{22}q_{22} - C_{32}q_{32}$$
$$+ P_a(q_{13} + q_{23} + q_{33}) - C_{13}q_{13} - C_{23}q_{23} - C_{33}q_{33}$$

subjected to the following totality constraints,

$$q_{11} + q_{21} + q_{31} \leq Q_1$$
$$q_{12} + q_{22} + q_{32} \leq Q_2$$
$$q_{13} + q_{23} + q_{33} \leq Q_3$$

Up to this stage, the above problem is traditionally known as least-cost linear programming model, wherein, the final outcome gives us the optimum quantities to be supplied from the specific source to the specific user. Using such optimum quantities in the previously mentioned demand curves, one can arrive at optimum pricing policy for water allocation. However, introducing socio-economic policy constraint,one can formulate price elasticity. As mentioned by Clausen, such constraint includes

$$K = N_mE_m + N_aE_a + N_iE_i$$

where

K = constant

E_m, E_a, E_i = price elasticity in municipal, agricultural and industrial waters,

N_m, N_a, N_i = weighing factors for municipal, agricultural and industrial waters.

These weighing factors are computed from the following relationship:

$$N_m:N_a:N_i = P_m(q_{11} + q_{21} + q_{31}):P_a(q_{12} + q_{22} + q_{32}):P_i(q_{13}+q_{23}+q_{33})$$

E_m = price elasticity for the municipal water

$$= \frac{\text{Projected Price - Existing Price}}{\text{Existing Price}}$$

Similarly, E_a and E_i are for agricultural and industrial water (10). Thus, with such cost optimization procedures coupled with the economic price elasticity concept, the above formulation tends to become an economic model rather than a traditional engineering cost minimization model. It is further possible to modify the above model by incorporating many other useful economic concepts described by James and Lee (25).

While trying to formulate a specific economic activity or to assess the economic impact of water resources projects, many economists developed economic models by analyzing economic data statistically. Wiebe, J.E., for example, used a typical multiple regression model of type $Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6$ to investigate the effects of water resources investments on regional income and employment (38). The variables in such an analysis are

X_1 = time in calendar year,

X_2 = per capita income,

X_3 = all spendable money income,

X_4 = total employment,

X_5 = capital invested in manufacturing,

X_6 = investments in dams, steam plants and reservoirs.

The regression coefficients b_1, b_2, b_3, b_4, b_5 and b_6 are estima ed for counties near and away from the Tennessee Valley Authority (TVA) projects. The statistical t tests on these estimated regression coefficients reveal that, in addition to the time factor, the investments in water resources have significant influence in estimating the changes in incomes, employment and opportunity function (38). Thus, the economic model of the above type is developed and used for examining the regional economic impact of water resources projects.

Recently, the economic return of recreational water bodies is formulated in many economic models. These economic models try to develop a utility function (or demand model) relating associated economic commodities based again on the statistical data analysis. With such procedure, Reiling and et al have developed the following demand model for the Willow Lake (45).

$$K^{*} = -6.534 + 0.002\ Y + 10.435\ P_1$$

$$P_1^{*} = 2.988 + 0.269K - 0.004K^2 + 0.00000017\ Y^2$$

$$q_1 = +0.759 - 0.0064K^{*} + .0064K + 0.06371P_1^{*} - 0.637\ P_1$$

where

q_1 = days of recreation per visit,

K = travel cost includes transportation, food expenditures lodging and camping fees,

P_1 = on-site costs,

Y = family income of the recreationist after taxes.

This demand function can be integrated with limits of integration as average on-site costs and critical on-site cost in dollars/day units. The result of such integration gives us a dollar value per visit. Then, finally the seasonal recreational value of the lake is obtained by multiplying the per-visit value by the estimated number of visits. In this manner, economic models are developed purely on the economic and statistical basis coupled with the data that are collected by distributing appropriate questionaires to the different users. Such an approach can be modified to extend these recreational economic models for multi-site recreational facilities. These recreational models can be useful in evaluating and planning the various improvement programs for the lake. Similar methodology is employed by Reynolds et al. in analyzing the Kissimmee River basin (46).

Engineering economic models, as contrasted with the above purely economic models, aim at minimizing the cost objective function subjected to the different process constraints. To illustrate such cost minimization process model, a classic example, studied and developed by Galler and Gotaas for biological filter is presented (17,18). As a first step, the important process variables are identified. For biological filters, recirculation rate $(\frac{Q}{I})$, temperature (T) hydraulic rate (Q), depth (D) and organic loading (L) are identified as independent variables and B.O.D. (Biochemical Oxygen Demand) removal as dependent variable. As a second step, a suitable nonlinear regression model is written as

$$\log L_e = A_1 \log L_o + A_2 \log(\frac{Q}{t}) + A_3 \log D + A_4 \log T + A_5 \log Q + B$$

where

A_j is the partial regression coefficients (j=1, 5)

L_e = B.O.D. in the effluent,

L_o = B.O.D. in the influent,

I = recirculation flow rate,

B = constant,

Q = flow rate,

T = Temperature,

In the next steps, the observational data of an adequate magnitude are collected for the above process parameters and the partial regression coefficients are computed. In addition, the multiple correlation coefficient for the above model is estimated. If this coefficient happens to be near one (say above 0.9), then the above nonlinear regression model is accepted. Based on the data used by Galler and Gotaas, the interrelationship between the process variables is obtained as

$$L_e = \frac{0.31\ L_o^{1.19}\ (\frac{Q}{I})^{0.28}}{(1+D)^{0.67}\,T^{0.15}\,(Q)^{0.06}}$$

This formulation has a multiple regression coefficient as 0.974 and, thus, is preferred to other formulations. The above equation is basically a performance equation which can be used for design purposes. However, this design is empirical but not optimal from an economic standpoint. Therefore, to arrive at optimum process variables (with minimum process cost), an objective cost function for the whole system of trickling filter is formulated with the process limitations and the above interrelationships as constraints. The final form of these formulations is given below

Cost objective function for a biological filter (17, 18),

$$C = [(C_1\pi WaD/27) + (2C_1\pi WaD/27) + (C_1\pi W^2D/27) + (C_2\pi a^2) + (C_3\pi a^2D/27) + (2C_4a) + (\frac{r}{C_6+C_7})]\,\lambda + [C_5 i(8.34)(365)(r)(D+1)/2.65P]$$

subjected to the constraints,

$$\ln L_e = \ln K_1 + 1.19\ \ln(iL_i + rL_e) - 0.78\ \ln(i+r) - 0.67\ \ln\ (D+1) - 0.25\ \ln(a)$$

$$0 \leq r \leq 4\ i$$

$$3 \leq D \leq 10$$

$$10 \leq a \leq 100$$

where

W = wall thickness,

a = radius of filter,

D = depth of filter,

F = freeboard above filter media in ft.,

r = recirculation flow,

i = incoming flow,

P = pump efficiency,

C_i = cost coefficients,

λ = capitol recovery factor,

π = 3.1415.

After converting the cost criteria into the above formulation, a suitable mathematical optimization technique called the cutting plane technique (a modified form of steepest gradient method) is used to arrive at the optimum values of number of filters, diameter, depth of biological filter and recirculation ratio. These values are, in turn, expressed in graphical form so that one can obtain the required optimum design values of trickling filter for a specific degree of B.O.D. removal. Thus, as can be seen through these specific examples, the engineering economic models coupled with mathematical optimization techniques select the process variables in such a way that the cost of the total system or process is optimum.

Sociological and Political Models:

In addition to the conventional economic analyses with ecological and many other factors, socio-political considerations also play an important role in setting water resources planning guidelines. Therefore, recently many efforts were concentrated in developing social and political models. These models possess many distinct characteristics. First of all, socio-political models that exist today are still in a qualitative stage (the same stage the ecological models were in a decade ago). As a result, most of these models are not formulated in terms of mathematical relationships but are expressed in terms of qualitative diagrams and flow charts of various social and political interactions. Secondly, these models basically explain the behavior, interrelationships and implications of the socio-political system based on the related decisions made in the past. In other words, these models try to analyze only past decisions in light of social-political considerations without developing generalized predictive mathematical relationships between system variables. Thirdly, these models can be better classified as conceptual models than conventional mathematical models. Recently, efforts were made to quantify these qualitative discussions regarding social and political decisions. In order to incorporate these social and political factors into the overall planning process, it is suggested to assign weights proportional to the degree of social and political support for water planning alternatives. The water resources scheme which is favored in all the technical, political, social and ecological respects (in terms of these wts.) is then finally planned.

While discussing social system models to be considered in the modern planning process, Mayer, R. R. (37) presented

1. a parsonian model of microcollectivity,
2. Ramsoy's model of the complex macrosystem,
3. Blau's concepts of the exchange system, and
4. Warren's model of the interorganizational field.

As mentioned earlier that these models are nothing but a detailed qualitative discussion of how different groups of society behave in different fashions depending on the nature of their authorative position. It is expected that such a detailed qualitative discussion becomes a stepping stone for developing more useful quantitative social models which do not exist today.

Another effort by Burke III, Heaney and Pyatt looks at the social aspects of water resources planning in Bow River Valley(7). In such a study, again different social factors like local support, social controversies, mutual accomodation, social interferences, fairness are only discussed without establishing mathematical relationships. The authors confess frankly that "their discussion of social models complicate matters in all ways. However, such is the nature of the beast; social decisions are harder to make. It is an effort that must be undertaken since the requirement for making social choices will not disappear even though existing tools are inadequate for that purpose".

In spite of tremendous qualitative inputs to the discussion of social and political interactions, fortunately some recent efforts are directed toward the quantification of these factors. In such methodology, the weighing matrixes are formed for different planning strategies and weights are assigned for different political and social considerations. Combining all these weights for economic, technical,social, political factors, a ranking procedure is developed for the alternatives in question. Such a procedure is recently demonstrated for evaluating water supply alternatives on a regional basis (35,49). Instead of forming these nonmathematical weighing matrixes of socio-political factors, another approach is to explore likely decisions by introducing a set of political weights in the net benefit function as

$$\Sigma W_i NB^i(X) \geq D^i$$

where

W_i = set of political or socio-political weights,

$NB^i(x)$ = net benefit function in location i in terms of variable X

D^i = the assigned value to the location i in dollars (46)

Considering such functional relationship, the solution of the overall optimization problem (resource allocation or cost minimization etc. etc.) for a specific set of political weights will be a pareto-admissible (14). Although it can be argued that the weights are decided upon by some kind of subjective value judgment, it appears that the above quantitative approach may be further handled in computerized simulation procedure to minimize, to some extent, the subjectivity associated with the weighing factors (19). Thus, as far as the current state of art of social and political models is concerned, the weighing matrix procedure coupled with linear or nonlinear programming techniques seems to include adequately the social and political aspects of water resources planning in a quantitative manner.

Modeling the technological and environmental factors:

In this category, the water systems are considered from an engineering standpoint and thus, efforts are concentrated on developing a predictive model which in turn can be implemented for operational purposes. For simplicity, these engineering efforts can be conceptually broken down into two broad technical categories; one is related to water quality models and the second is in the area of water quantity models. Since the water quality and quantity characteristics of water bodies are functions of various environmental factors (such as physical chemical and biological aquatic interactions, topographic characteristics and hydrologic behavior of the basin), these technological models (water quality-quantity models) are developed with special emphasis on these environmental interactions. From technical viewpoints, these models are further classified as

1. water quality models,
2. hydraulic models, and
3. hydrology models.

The basic difference in the approach of these models is that water quality models consider the interplay of various physical, chemical and biological processes in the aquatic system; hydraulic models are generally based on the hydrodynamic properties of the water system and hydrology models consider the water budgeting procedure of accounting precipitation, evapotranspiration, storage, seepage, atmospheric water transport and finally various runoff quantities. The detailed discussion of these models is attempted in the following section:

Water Quality Models:

The basic purpose of water quality models is to represent the various reactions of aquatic environment in mathematical terms so as to predict the possible changes in the water quality due to the changes in different environmental inputs. Such models appear to be very useful in regulating the pollutional inputs to the water bodies.

The approach of developing these generalized water quality models include the following basic steps:

1. selecting the appropriate water quality parameters for a specific water system,
2. identifying various interactions (i.e. sources and sinks of water quality parameters),
3. formulating these interactions in terms of the selected water quality parameters by either continuity equation or momentum equation or mass balance principles,
4. arriving at the final analytical or numerical solution relating

the appropriate quality parameter with the rate coefficients representing different interacting processes and

5. verifying the predicted values (obtained by the analytical solution) with the actual observed values.

The water quality modeling procedure invariably starts with

$$\frac{\partial c}{\partial t} = \nabla \cdot j \pm \Sigma s$$

where

$\nabla\cdot$ = mathematical operator $\left(i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}\right)$,

c = concentration of water quality parameter,

t = time,

j = flux = $E\frac{\partial c}{\partial n} - U\cdot c$

n = dimensions,

E = dispersion coefficient,

U = velocity,

Σs = sum of sources and sinks (39)

For a specific water system, for example a stream, a useful operational water quality parameter is first selected. For most of the efforts reported so far, water quality models are developed for nonconservative substances like dissolved oxygen, and biochemical oxygen demand (B.O.D.) although modifications can be made to include conservative parameters also. Considering the dissolved oxygen as the net resulting water quality parameter, an oxygen balance of the stream (with various sources and sinks of oxygen) transforms the above generalized continuity equation into the following form (54).

$$\frac{\partial C}{\partial t} = \frac{Q}{A_x}\ \frac{\partial C}{\partial x} + K_a(C_s - C) + P(x,t) - K_n N_x - R(x,t) - S(x,t) - K_d L_x$$

where

$\frac{Q}{A_x}\frac{\partial X}{\partial x}$ = advective transform of concentration in x direction

$K_a(C_s - C)$ = reaeration term,

$P(x,t)$ = photosynthetic term,

$K_d L_x$ = = deoxygenation process,

$K_n N_x$ = nitrification,

$R(x,t)$ = respiration and

$S(x,t)$ = benthalic demand,

Further analysis made by O'Connor (54) on the differential equation (with most of the processes incorporated in oxygen balance) gives the distribution of dissolved oxygen concentration as

$$D(x,t) = D_o e^{-\frac{K_a x}{U}}$$

$$+ \frac{K_d L_o}{K_a - K_r} \left[e^{-\frac{K_r x}{U}} - e^{-\frac{K_a x}{U}} \right]$$

$$+ \frac{K_n N_o}{K_a - K_r} \left[e^{-\frac{K_n x}{U}} - e^{-\frac{K_a x}{U}} \right]$$

$$+ \frac{R}{K_a} \left[1 - e^{-\frac{K_a x}{U}} \right]$$

$$- P_m \left[\frac{2p}{K_a} \quad \left(1 - e^{-\frac{K_a x}{U}}\right) \right]$$

$$+ 2 \sum_{n=1}^{\infty} \left[\frac{A_n}{\sqrt{(K_a)^2 + (2\pi n)^2}} \cos \left[2\pi n(t - p/2) - tg^{-1} \left(\frac{2\pi n}{K_a} \right) \right] \right]$$

$$- 2e^{\frac{K_a x}{U}} \left[\sum_{n=1}^{\infty} \frac{A_n}{\sqrt{(K_a)^2 + (2\pi n)^2}} \cos \left[2\pi n \left(t - p/2 \frac{x}{U}\right) - tg^{-1} \left(\frac{2\pi n}{K_a} \right) \right] \right]$$

where

$D(x,t)$ = dissolved oxygen conc. at distance x units,

D_o = initial dissolved oxygen concentration,

K_a = reaeration rate constant,

x = distance in length units,

U = average velocity in x direction,

K_d = deoxygenation rate coefficient in B.O.D. bottles,

L_o = initial ultimate B.O.D. input,

K_r = deoxygenation rate in the river,

K_n = nitrification rate constant,

N_o = initial concentration of nitrogen input,

R = respiration rate,

P_m = amplitude of the photosynthetic wave,

p = period of the photosynthetic wave,

t = time,

A_n Fourier Coefficients

From an operational standpoint, this solution predicts the spatial and time distribution of dissolved oxygen concentration, taking into account the possible physical, chemical and biological interactions. This solution can be further used to control the pollutional load to maintain the design level of dissolved oxygen in the stream. The various steps of this formulation are applied to analyze the oxygen deficits of the Sacramento River, Elk Creek, Codorus Creek, Holston River, Wabash River, Scioto River and East River (54) and a close agreement between predicted and observed D.O. and B.O.D. profiles is obtained for these rivers. It is to be noted here that the above formulation assumes

1. one dimensional transport,
2. steady state conditions,
3. uniform flow and areal characteristics,
4. first order decay rates, and

5. nonconservative water quality parameters.

This approach of considering the longer lengths of river and developing an analytical solution for the distribution of water quality parameters is technically known as continuous solution approach. The second approach wherein the water system is divided into numbers of finite sections and analyzing each section separately is known as, finite section approach.

In finite section approach, each section is assumed to be completely mixed without any directional concentration gradients. Under this assumption, the mass balance equation for ith section is written as (15),

$$V_i \frac{dc_i}{dt} = Q_{i-1,i}\left[\alpha_{i-1,i}c_{i-1} + \beta_{i-1,i}c_i\right] - Q_{i,i+1}\left[\alpha_{i,i+1}c_i + \beta_{i,i+1}c_{i+1}\right]$$

$$+ E'_{i-1}(c_{i-1}-c_i) + E'_{i,i+1}(c_{i+1}-c_i) - K_iV_ic_i + W_i \pm \Sigma S_i;\ i = 1,2\ldots N$$

V_i = volume of segment i,

C_i = concentration of water quality parameters in section i,

$Q_{i,i+1}$ = flow relationship between section i and i+1,

$E'_{i,i-1}$ = bulk dispersion coefficient over two adjacent sections i and i-1,

$\alpha_{i,i+1}$ = dimensionless mixing coefficient between i and i+1,

ΣS_i = sum of sinks and sources for ith section

$\beta_{i,i+1} = 1 - \alpha_{i,i+1}$

Assuming steady-state condition and after evaluating numerical coefficients of the above difference equation, the solution can be obtained either by implicit iteration method or by solving simultaneous equations in matrix form. Such solution provides concentration of the water quality parameters in all the sections based on the boundary conditions of known concentration levels of the first and last sections. It is further demonstrated that consecutive multi-stage water quality reactions can be formulated by such finite section approach (15). Similarly, two dimensional steady state water quality models like

$$\frac{\partial c}{\partial t} = 0 = - \frac{\partial}{\partial y}(uc) - \frac{\partial}{\partial y}(vc) + (\frac{\partial}{\partial x}(E_x \frac{\partial c}{\partial x})) + (\frac{\partial}{\partial y}(E_y \frac{\partial c}{\partial y})) - K(x,y)c$$

and one dimensional time varying model like

$$\frac{\partial L}{\partial t} = - \frac{1}{A} \frac{\partial}{\partial x} (QL) + \frac{1}{A} \frac{\partial}{\partial x} (EA \frac{\partial L}{\partial x}) - K_r L$$

$$\frac{\partial c}{\partial t} = - \frac{1}{A} \frac{\partial}{\partial x}(Qc) + \frac{1}{A} \frac{\partial}{\partial x}(EA \frac{\partial c}{\partial x}) + K_a(c_s - c) - K_d L + P - R - B$$

can also be handled by either finite section approach or finite difference technique. In a nutshell, all the water quality models described so far attempt to incorporate the possible water quality variables into a generalized differential equation form the solution of which provides the spatial and time distribution of water quality parameters in terms of various rate coefficients. Thus, with the help of such water quality models, the complex problem of water quality forecasting reduces basically to measuring the appropriate kinetics coefficients in the laboratory or in the field for a particular water system and then plugging these values into the generalized solution to arrive at the planning guidelines for maximizing the beneficial use of water systems.

Although traditionally the water quality analyses are basically geared to the various aspects of the fundamental Streeter Phelp oxygen sag equation (i.e. genearlized solution with only deoxygenation and reaeration terms), many assumptions and simplifications are found to be inadequate for some locations. As a result, different modifications in general approach are suggested and developed. Such efforts have led to the development of

1. probabilistic water quality models,
2. spectral models for analyzing water quality data and
3. empirical statistical models connecting key water quality parameters

It is hypothesized that since the dissolved oxygen levels are the net results of many complex intermediate interactions, the behavior of water quality parameters may be probabilistic and may not be deterministic as implied in the previously described formulations. Based on this conceptual hypothesis, Loucks and Lynn (28) tried to apply probabilistic techniques to the behavior of dissolved oxygen levels in the stream. In such a study, based on the streamflow data and sewage flows inventories, they first established the transient probabilities that the river flow and sewage flows are in the particular state if given their values in the previous state. Similarly, establishing transient probabilities for the dissolved oxygen parameter, the probability distribution of the resulting D.O. concentration is obtained using the Streeter Phelp oxygen sag equation for four different probability models. The final results are represented in graphical form which provide probability numbers showing that dissolved oxygen levels are less than specific value in one, two or three consecutive days. This methodology is successfully applied to the data of a comprehensive sewage study of Tompkins County, New York, and has advocated the probabilistic stream standards rather than policies based on the deterministic approach. Working in the same general area of probabilistic stream quality models, Kothandaraman, demonstrated that D.O. levels in the Ohio River at six different locations possess normal probability distribution (28). Similarly, the variations of deoxygenation and reaeration rate coefficients are established by sensitivity analysis. The Monte Carlo method is applied to generate random numbers representing D.O. levels based on the observed properties of the distributions of the rate coefficients. Results of the probabilistic model are compared with Streeter Phelps equations, Camp's equation and actual field measurements, and it is demonstrated that the range of percentage errors of probabilistic model is the least among the three tested methods and thus, in this manner, the merit of such a probabilistic water quality model is proven.

Spectral models are basically used to first analyze the sequential relationships between water quality parameters and then to understand the cause-effect relationships of the different processes involved. These statistical models work on the available water quality time series data to provide statistical parameters (like serial correlation coefficients, covariance, spectral density, coherence, phase angle and response function for different frequencies). The variation of these statistical parameters is then correlated to the inherent characteristics (like periodicity, markov dependence, trend) of the time series data. Recently, these models were applied in analyzing variability of waste treatment plant performance and exploring the characteristic behavior of the components of the hydrologic cycle of the United States (13,47). The general procedure and the computational steps involved in these analyses are shown in Figure 2, 3 and 4. These steps provide us the useful information related to

1. the dependent structure within and between time series,
2. correlation structure of two data sets in ordinary and in frequency domain and
3. the degree of systematic pattern or randomness involved in the original time-series data

These characteristics in turn can be used in the development of the stochastic models of the following type (47).

$$P(mt + a \leq Xt \leq mt + b) = \int_a^b 90.488\left(1 + \frac{x}{3.054}\right)^{2.475}\left(1 - \frac{x}{57.543}\right)^{46.65} dx$$

where

Xt = time series for atmospheric divergence for Eastern Region of the United States (i.e. random variable Xt)

mt = deterministic part of stochastic time series of atmospheric divergence

$$= 3.550 - 1.770 \cos\left(\frac{\pi t}{6}\right) + 1.079 \sin\left(\frac{\pi t}{6}\right)$$

$$+ 1.028 \cos\left(\frac{\pi t}{3}\right) + 0.830 \sin\left(\frac{\pi t}{3}\right)$$

FIGURE 2

General Procedure for Analyzing Individual Time Series

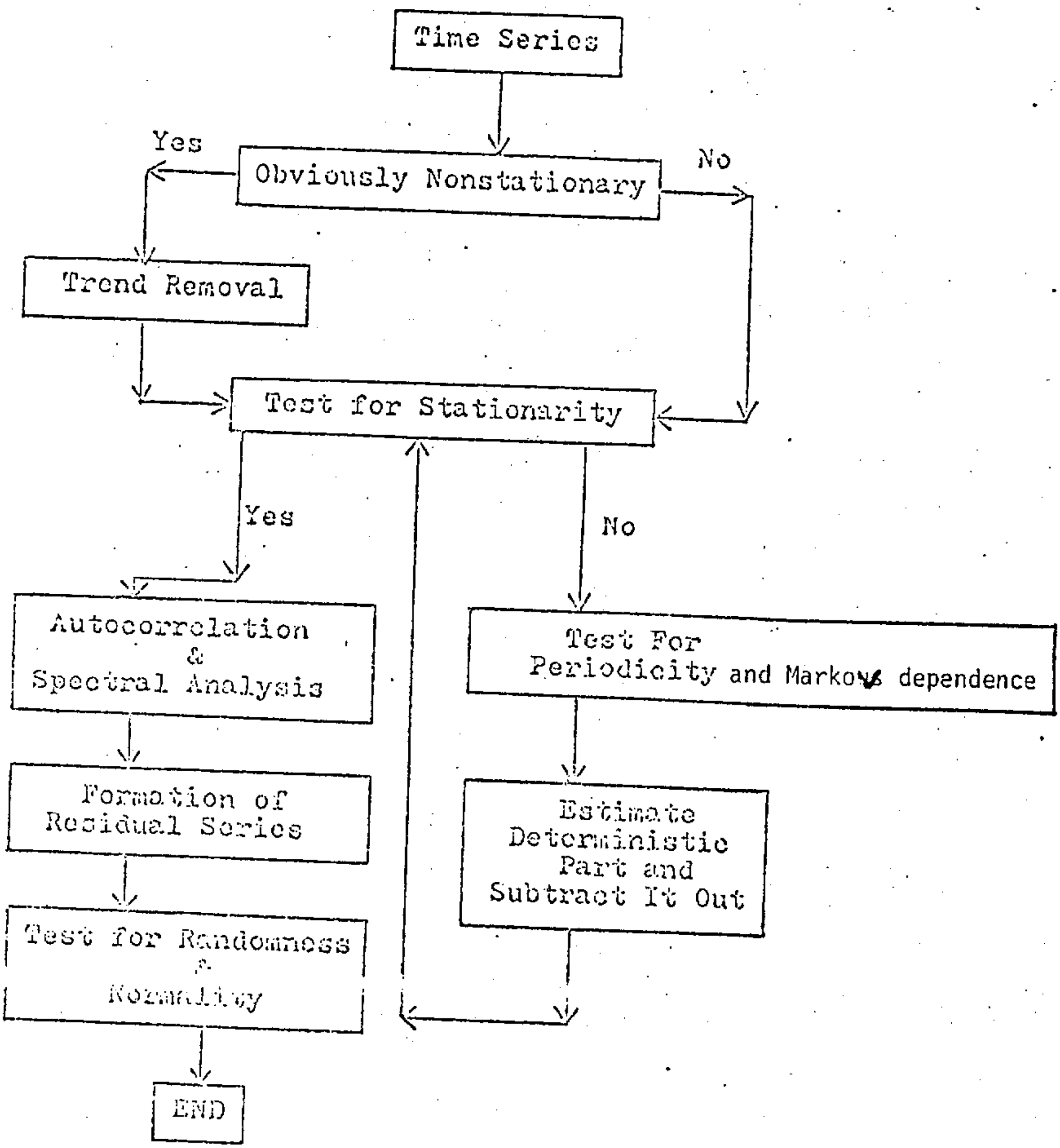


FIGURE 3 A Flow Diagram of the Statistical Methodology

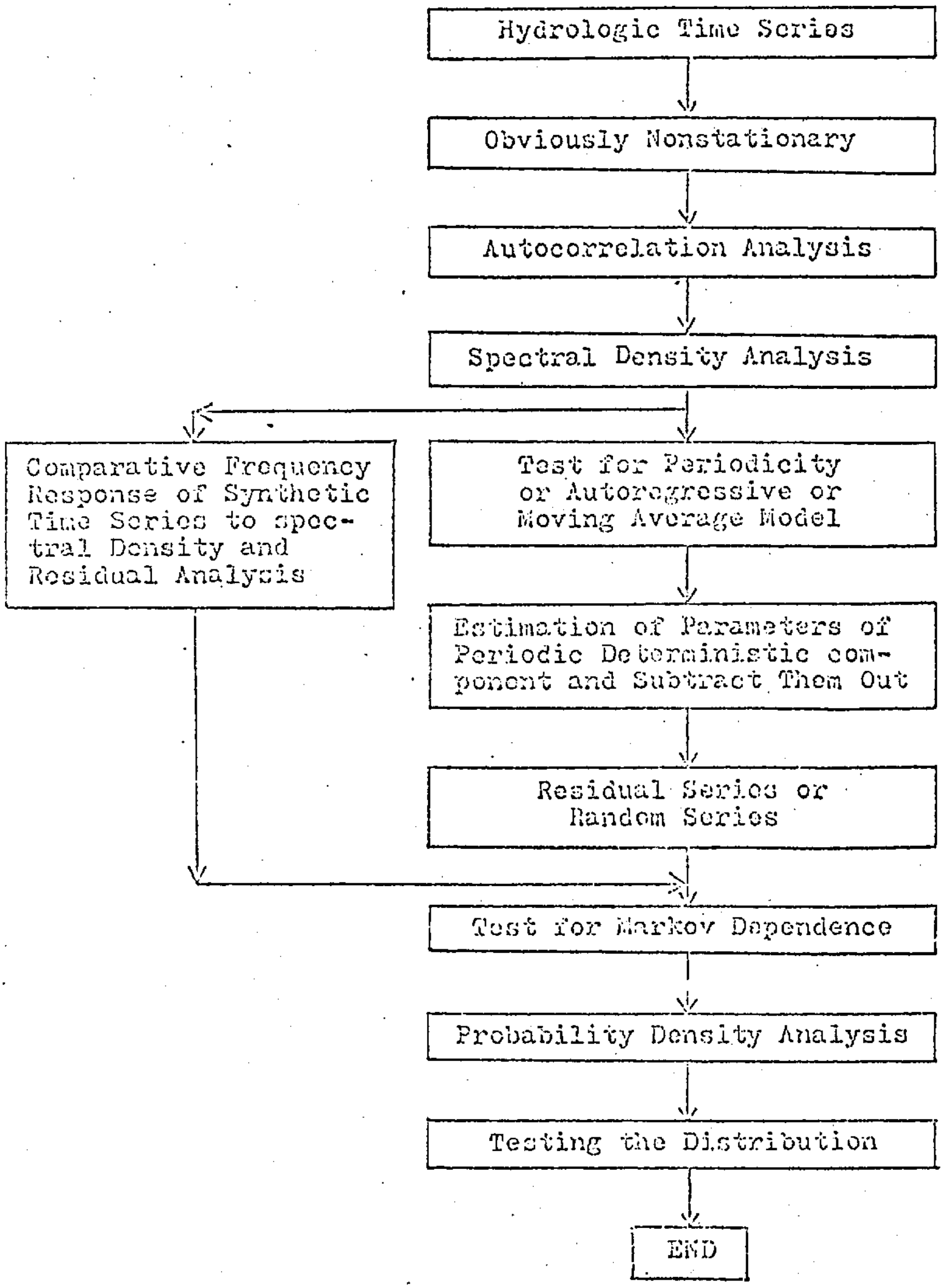


FIGURE 4

FLOW CHART OF COMPUTATIONAL STEPS FOR DATA ANALYSIS

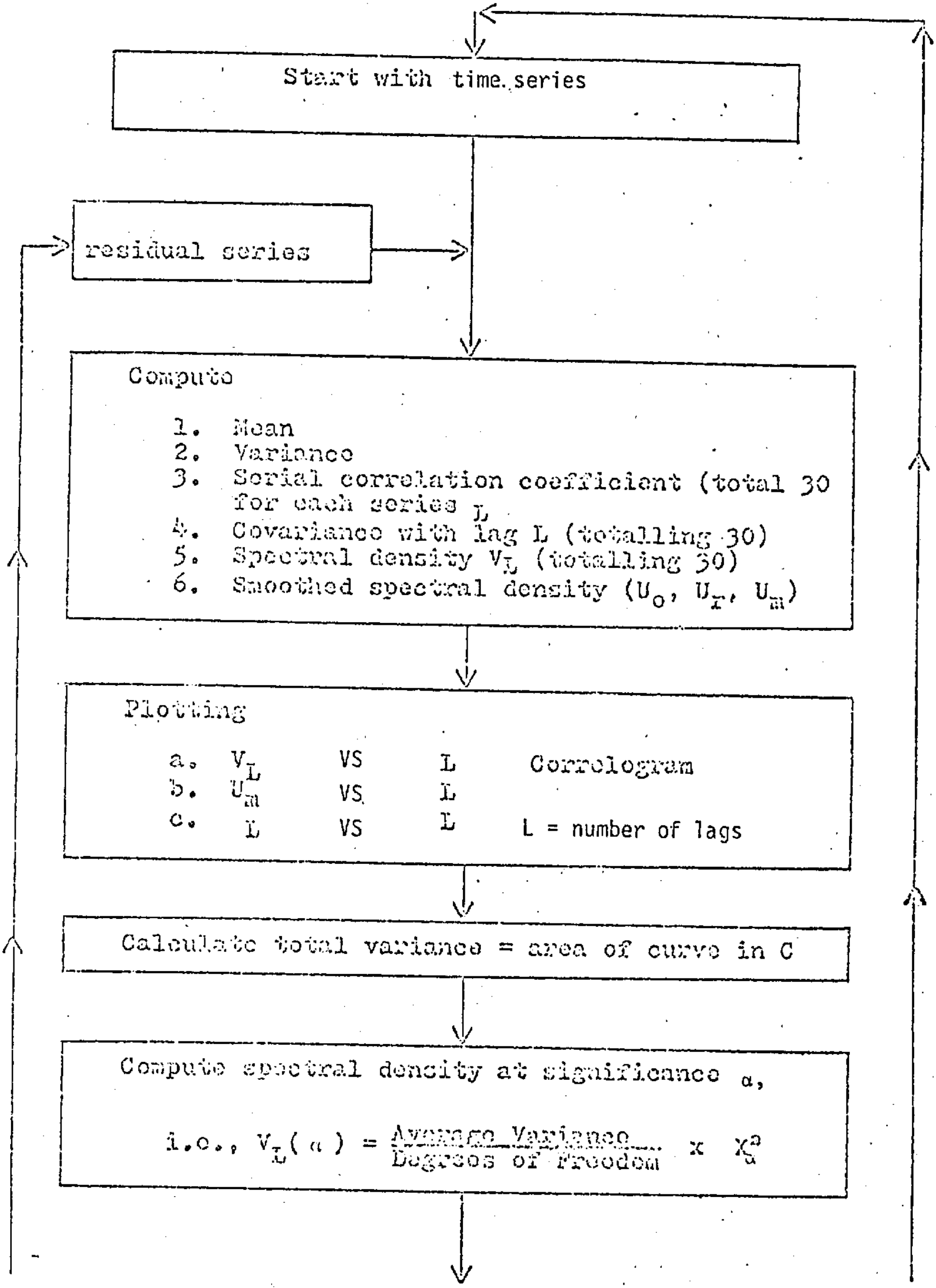


FIGURE 4 (Cont'd)

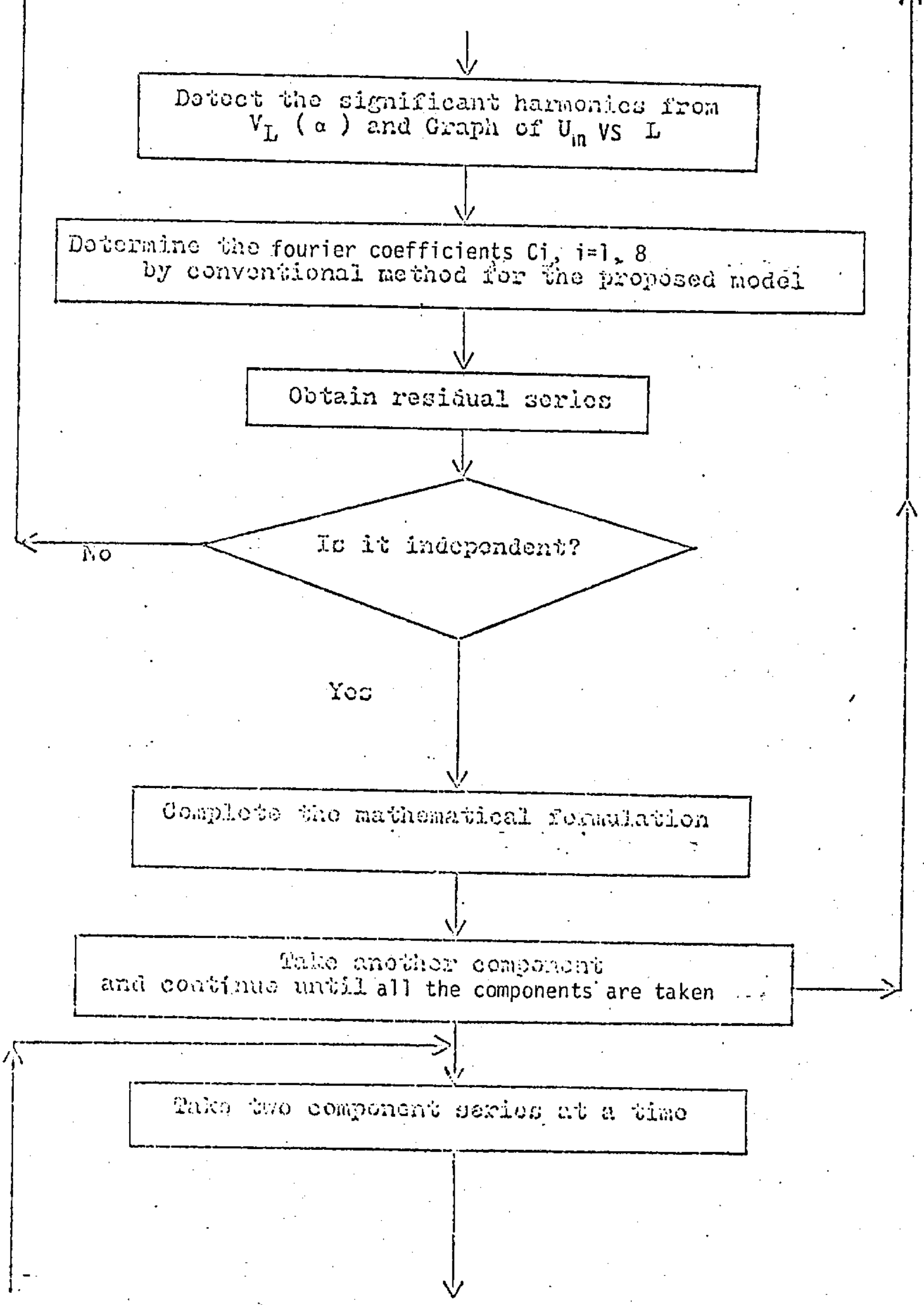


FIGURE 4 (Cont'd)

Compute

1. Autocorrelation coefficient of Lag L
2. Cross-correlation functions of pair of series
3. Fourier Cosine Transform (C_r')
4. Power spectra (U_r)
5. Cospectrum (C_r)
6. Quadrature spectrum (Q_r)
7. Coherence (H_r)
8. Phase angle
9. Response function spectrum

Take another pair and continue until all the combinations are covered

End

$$+ 0.245 \text{ Cos}\left(\frac{\pi t}{2}\right) + 0.525 \text{ Sin}\left(\frac{\pi t}{2}\right)$$

$$+ 0.224 \text{ Cos}\left(\frac{\pi t}{1.5}\right) \quad 0.075 \text{ Sin } \left(\frac{\pi t}{1.5}\right)$$

a, b are constants

$P(mt + a \leq Xt \leq mt + b)$ = probability that the random variable Xt lies between mt + a and mt + b.

The basic assumption here is that the random variable is the sum of the deterministic and random part. In this particular case,after performing various statistical tests on the time series data to detect the presence of trend, periodicity and Markov dependence, it is found that the given time series does not possess trend or Markov dependence characteristics and therefore, the deterministic part contains only periodic terms. Thus, based on the above discussion it can be said that spectral models are basically stochastic models wherein spectral and cross spectral techniques are employed to detect and formulate the characteristics of the time series data.

Although the above described methods are regarded as vigorous mathematical analyses of stream dynamics, many practical engineers feel that the natural processes are too complex to be handled by mathematics alone. As a result, many empirical relationships are developed based on sound engineering judgment coupled with long practical experience for forecasting and water planning purposes. For example, an empirical model suggested by Reid, G. W. (44) for storm drainage as written as

$$Y_2 = 4.8 + 0.082X_2 + 0.48X_8$$

$$Y_5 = 2.38 - 0.188 \ln X_1 + 0.310 \ln X_{10} \text{ and}$$

$$Y_6 = 2.90 + 0.00003X_1 \quad -.0001X_3 - 0.0137X_8 - 0.741X_{11}$$

where

X_1 = population,

X_2 = population density ,

X_3 = number of households,

X_8 = commercial establishment,

X_{10} = streets,

X_{11} = environmental index,

Y_2 = B.O.D.,

Y_5 = total nitrogen,

Y_6 = total phosphorous (44)

Another interesting empirical relationship developed by Reid, G. W. (44) for the eutrophication process relates the nutritional dilution required with eutrophication parameters as shown below:

$$Q_n = \frac{Z \cdot P}{F_n RQS_n} (1 - TL_n - 1.44 (1-TL_L)) \times (TL_L 3250)$$

$$Q_p = \frac{Z \cdot P}{F_p RQS_p} (1 - TL_p) - 0.27 (1-TL_L) (TL_L 1080)$$

where

Q_p or Q_n = nutritional dilution required,

Z = relative portion impounded and effected by RQS level,

P = population in millions,

TL_p or TL_n = phosphorus or nitrogen removal level expressed as a decimal,

F_p or F_n = BOD/P ratio,

TL_L = BOD removal level expressed as a decimal,

RQS_p and RQS_n = acceptable level.

The criticism that is generally heard regarding these empirical models is that the approach of these models is not generalized and thus, may not be helpful to any other situation. However, for setting planning guidelines on a regional basis, these empirical models may be more handy than the generalized solution of vigorous mathematical formulation.

Hydraulic Models:

As the name suggests, these models are formed to predict the hydraulic characteristics of water systems. These characteristics can predict

1. water levels in the water system and
2. velocity, hydraulic gradient and energy of the flowing water.

The approach of developing these models starts with a generalized hydrodynamic equation (such as Navier Stoke's equation or continuity or momentum or energy equation.) Then, this generalized equation is simplified for a specific type of water movement (like gradually varied flow or unsteady channel flow etc. etc.) and a differential equation or a partial differential equation is obtained for the hydraulic parameter in question. For example, as presented by Sinha, L.K. (52), differential equation for determining a change in depth of water with space $(\frac{dy}{dx})$ is given as

$$\frac{dy}{dx} = \frac{SO - SE}{1 - \frac{\alpha Q^2 T}{gA^3}}$$

where

y = depth of water or stream depth,

x = distance along the channel bed,

SO = slope along the stream bed,

SE = energy gradient,

α = velocity head coefficients,

Q = discharge through the control structures,

T = top width of the channel cross-sectional area of the channel.

The solution of this differential equation is, in turn, used successfully to simulate the water surface elevation and storage characteristics of channelized river system (52). Another example of a hydraulic model is the EPA's water receiving model (1). In this model, which is similar to the formulation of the change in depth of water $(\frac{dy}{dx})$ in the above model, the equation of motion for a one dimensional channel is written as

$$\frac{dv}{dt} = \frac{V \partial V}{\partial X} - g\frac{\partial H}{\partial X} - gSf + gSw$$

where

V = velocity,

t = time,

X = distance

H = water surface elevation measured from the datum plane,

g = gravitational acceleration,

Sf = energy gradient,

Sw = wind stress (30)

After determining the constants of the equation, the solution of the above equation gives the flow rates in each channel. Based on various inputs and outputs, the rise and fall of the water surface (head) can be determined at each junction. By continuing such procedure step by step with different boundary contitions, the hydraulic characteristics of the different links and of the overall system are obtained (30). As compared to the generalized water quality formulations, at the present time, the hydrodynamic approach of determining hydraulic characteristics is more acceptable because of the less unidentified phenomenon and close agreement with measured values.

Hydrology Models:

These models, as contrasted with hydraulic and water quality models, try to estimate the hydrologic parameter which is a net result of many other hydrological and meteorological sub-systems. In most hydrologic studies at local, subcontinental or global levels, an accounting of hydrologic components (with occassional modified and complicated form of the basic budgeting procedure) is addressed to understand quantitatively the hydrologic characteristics of the given region. Instead of choosing arbitrarily the region under investigation, it is convenient and desirable in many instances to select a region which happens to be a drainage basin or a watershed. Although according to Webster's definition, a watershed is a topographic divide that sheds water into two or more drainage basins, and a watershed is used synonymous to the drainage basin which is defined as a watershed that collects and discharges its surface streamflows through one outlet. The main advantages of selecting a watershed for hydrologic investigations are:

1. the data collection task is greatly simplified since only one outlet is involved in monitoring streamflows,
2. various methodologies can be developed and conveniently tested and calibrated (if necessary) by measuring the outlet streamflows.
3. Mass-balance equations can be used to understand the interactions of input, output and storage factors of the given watershed.

Realizing these and many other possible advantages of watershed analysis various investigators have studied large and small sized watersheds from different and perhaps unique hydrologic viewpoints. As a result, there exist varieties of hydrology models that can be applied to generate different types of information suitable for wide ranges of application. Among the long list of these numerous models, the major hydrologic watershed models include:

1. Stanford Watershed model,
2. Illinois Hydrologic Model (called WES and IHW Hydrodynamic Model).
3. Harvard Model (Thomas-Fiering Model),
4. HEC Model,
5. Travelers Research Center Models (Statistical Empirical Models)
6. Linear-nonlinear System Response Model for the overland flow,
7. Hydrometeorological approach,
8. USDA HL-70 model of watershed hydrology.

It is to be noted here that all these models are developed on different principles, assumptions and mathematical types (like stochastic empirical, deterministic, empirical etc. etc. Again, thinking that the development procedures of the hydrologic models would be clearer by pointing out the fundamental concepts associated with these models, the following section is devoted to present very briefly the salient features of these models.

The Stanford Watershed Model (developed by Crawford and Linsley) is also a simulation technique to develop a model structure for the terrestrial branch of hydrologic cycle. Considering hydrologic processes at land surface (such as infiltration, overland flow, groundwater flow and evapotranspiration), channel system and snowmelt phenomenon, streamflows for drainage basins of the Russian River, French Broad River, South Yuba River, Napa River and Beargrass Creek (drainage areas ranging from 0.7 to 1342 sq. miles) are computed using precipitation and various coefficients in mathematical functions representing these hydrological processes (12). Computational steps, in a nutshell, include the identification of subprocesses, establishing the mathematical formulations for various hydrologic subprocesses and performing the sensitivity analysis on the coefficients to arrive at reasonable ranges of coefficients to tune up the model. (12).

Another approach that is taken by Kareliotis and Chow related to the e examination of hydrodynamic characteristics of the watershed flows. In this approach, nonlinear differential equations based on continuity and momentum principles are formulated and then solved by the method of characteristics (27). The output of this model is compared with the experimental laboratory data collected from the University of Illinois watershed experimentation system (WES).

The Harvard Model, put forward by Thomas and Fiering, performs statistical analyses on historical data of the watershed (16). Using the statistical characteristics reflected in serial correlation coefficients, mean, standard deviation of the past recorded data, synthetic streamflows are generated with the same statistical properties observed in past history. In addition to the estimation of the statistical parameters, it also includes stochastic, probabilistic and deterministic rationales and formulations.

The HEC models, developed by the U. S. Army Corps of Engineers of HEC at Sacramento, California, deal with

1. the generation of flood hydrograph based on unit hydrograph theory, HEC-1 for example (3).
2. statistical analyses of recorded data to simulate the synthetic streamflows on a monthly and daily basis (4). Conceptually, this methodology is similar to the procedure of the Harvard Model with possible difference in the statistical formulations and
3. optimization of parameters to include effectively rainfall, snowfall, snowpack, snowmelt and runoff determinations.

This procedure is again on parallel lines with the Stanford Model of hydrograph synthesis with added capability of streamflow optimization, computations of design flood unifying hydrographs through channel, reservoir routing.

A series of statistically derived empirical models are generated by Travelers Research Center at Hartford, Connecticut, for estimating the magnitude and frequency of peak runoff from small, ungaged rural watershed of 20 square miles or less (5, 6). This methodology considers data samples of peak discharge, topographic parameters, hydrologic, climatic factors and physiographic soil characteristics of 493 watersheds with the average time of record of 18 years. After collecting these data sets, a framework with hydrologic and statistical reasoning coupled with a stepwise regression technique is designed to develop predictive equations expressing peak runoff as functions of various topographic, hydrologic-climatic and physiographic variables. After comparing the results of these equations with 31 state highway department design methods, this set of national equations appear to have equal predictive capability as other existing models.

While providing theoretical, mathematical and practical improvements in the basic theories of unit hydrograph and instantaneous unit hydrograph (IUH), a host of linear systems analysis techniques are developed by investigators at Purdue University and at MIT (5,6). In principle, these techniques evaluate the mathematical kernel function within the convolution integral equation of input-output variables. These techniques are applied to 55 watersheds (ranging in size from 2 to 300 sq. miles) in Indiana as well as two small drainage basins in Texas to approximate the rainfall-runoff phenomena. Although results obtained in these studies are encouraging, linear-nonlinear system response models are still in the mathematical and conceptual development stage and they may not be feasible from an engineering design point of view, until generalized transfer functions are selected based on simple, inexpensive techniques (6).

Another principle that is widely used by hydrologists and yields useful practical information, is mass balance concept. Using this concept with appropirate sets of numerical adjustments coupled with an interdisciplinary methodology, a hydrometeorological approach is developed to analyze hydrologic cycle on a subcontinental basis (47). In this approach, mass balance equations are formulated for terrestrial and atmospheric branches of the hydrologic cycle for 76 drainage areas of the United States. Using atmospheric vapor transport data these equations relate to the mean monthly precipitation, evapotranspiration, storage, runoff and atmospheric components for drainage areas varying from 58,000 sq. miles to 84,000 sq. miles. The success of this methodology is seen by comparing output values of evapotranspiration with widely accepted Thornwaite' values (47). This approach is also convenient to analyze various hydrologic processes on a global, continental, subcontinental and a microscale basis if atmospheric measurements are available.

A different viewpoint to develop a watershed model is consideration of agricultural characteristics of the watershed in estimating the parameters of the watershed. The particular approach is selected by Holtan and Lopez of the U.S.D.A. to formulate USDAHL-70 Model of watershed hydrology (22). In their methodology, water related agricultural parameters and coefficients are obtained from field experiments to develop empirical relationships for evapotranspiration, infiltration, deep seepage and routing coefficients for water movement in the soil characterizing the different hydrologic capacities of the soil types.

All these interdisciplinary models ultimately provide the information which can be used either in

1. optimizing the specific system, or
2. design of processes and operations associated with the water systems, or
3. operational control of system variables.

In addition, there is increasing trend to combine the concepts of these interdisciplinary models to formulate the multi-objective aspects of the water resources systems and then to apply different programming techniques to obtain the best values of decision variables under the given set of interdisciplinary conditions. Basic principles underlying these two important steps of modeling tasks are briefly discussed in the following section.

GENERAL METHODOLOGY OF OPTIMIZATION

Basically, the quantitative aspects of the optimization procedure include:

1. Mathematical model building.
2. Application of programming techniques to solve these models, and
3. The use of simulation and network theory to the process selection or network optimization

In formulating mathematical models, the first important step is to choose adequate and appropriate objective cirteria of the system. This can include either minimization of operational cost of a unit step or maximization of efficiency obtained from the process or minimization of the time involved in one particular operation in question or it can as well be a multi-objective criteria.. Among many such possible objectives, one or more for which quantitative information is available is selected. On the basis of this quantitative information, a mathematical equation is developed for chosen objectives. This equation can be based on either:

1. Addition of cost items encountered by variables as a function of these variables, or
2. Combining the variables with existing relationships betweentwthem to achieve certain objectives, or
3. Applying well-known principles, such as continuity equations, material and charge balances, conservation of momentum, or reaction kinetics, to the variables involved, or
4. Empirical correlations between dependent and independent variables.

Such a mathematical model for achieving a specific objective is technically known as an <u>objective function</u>. In addition to the relationships for achieving an objective, the variables themselves are generally interrelated. These types of internal mathematical relationships are designated as <u>constraints</u>. Thus, the final selection, in terms of these variables, has to satisfy constraint equations in addition to the objective function.

Based on the nature of the objective function and constraint equations, the following mathematical optimization techniques are widely used (9).

1. Linear programming
2. Integar programming
3. Parametric linear programming
4. Quadratic programming
5. Kuhn-Tucker's conditions
6. Lagrange's undetermined multiplier
7. Geometric programming
8. Dynamic programming
9. Search techniques
10. Simulation

These techniques are useful primarily in optimization procedures to find out optimal values of system variables. These are followed by a rigorous recursive procedure (algorithm) based on mathematical principles. To manage the large number of computations involved in these programming techniques, a high speed digital computer is generally built into the overall control system. These deterministic techniques (excluding probabilistic and stochastic) are briefly described in the following section. It is to be noted here that these techniques are a part of many recently reported advanced multi-objective programming techniques, like Generation Techniques, which rely on prior articulation of preferences and on progressive articulation of preferences (11).

A BRIEF DESCRIPTION OF AVAILABLE PROGRAMMING TECHNIQUES

Linear Programming: This technique is used for the problems concerning the optimum allocation of limited sources among competitive activities. The general mathematical statement of a linear programming model is represented as objective function

maximize or minimize $Z = C_1X_1 + C_2X_2 + C_3X_3 + \dots C_nX_n$

subjected to constraints of type

$$A_{11}X_1 + A_{12}X_2 + A_{13}X_3 + \dots A_{1n}X_n \leq B_1 \text{ (or } \geq B_1 \text{ or } = B_1)$$

$$A_{21}X_1 + A_{22}X_2 + A_{23}X_3 + \dots A_{2n}X_n \leq B_2 \text{ (or } \geq B_2 \text{ or } = B_2)$$

$$A_{m1}X_1 + A_{m2}X_2 + A_{m3}X_3 + \dots A_{mn}X_n \leq B_n$$

all $X_i > 0$, A_{ij}, B_n and C_n are constants

and X_1, X_2, X_3, ... X_n are decision variables like

1. Amount of sludge from unit 1, 2, 3, or
2. degree of removal from unit 1, 2, 3, etc. etc.

The final optimum values of decision variables are obtained by Simplex algorithm which is basically an iterative scheme for moving from one extreme point to an adjacent one until an optimal solution identifies itself. The methodology involved in the Simplex method is illustrated by the flow chart given in Figure 5 (53).

Here it is to be remembered that the above flow chart provides

(a) the means for locating an initial extreme point from which a convex set of solutions are explored.

(b) a way to move from one extreme point to another more attractive optimal solution without backtracking

(c) a flag to identify an optimal solution (53).

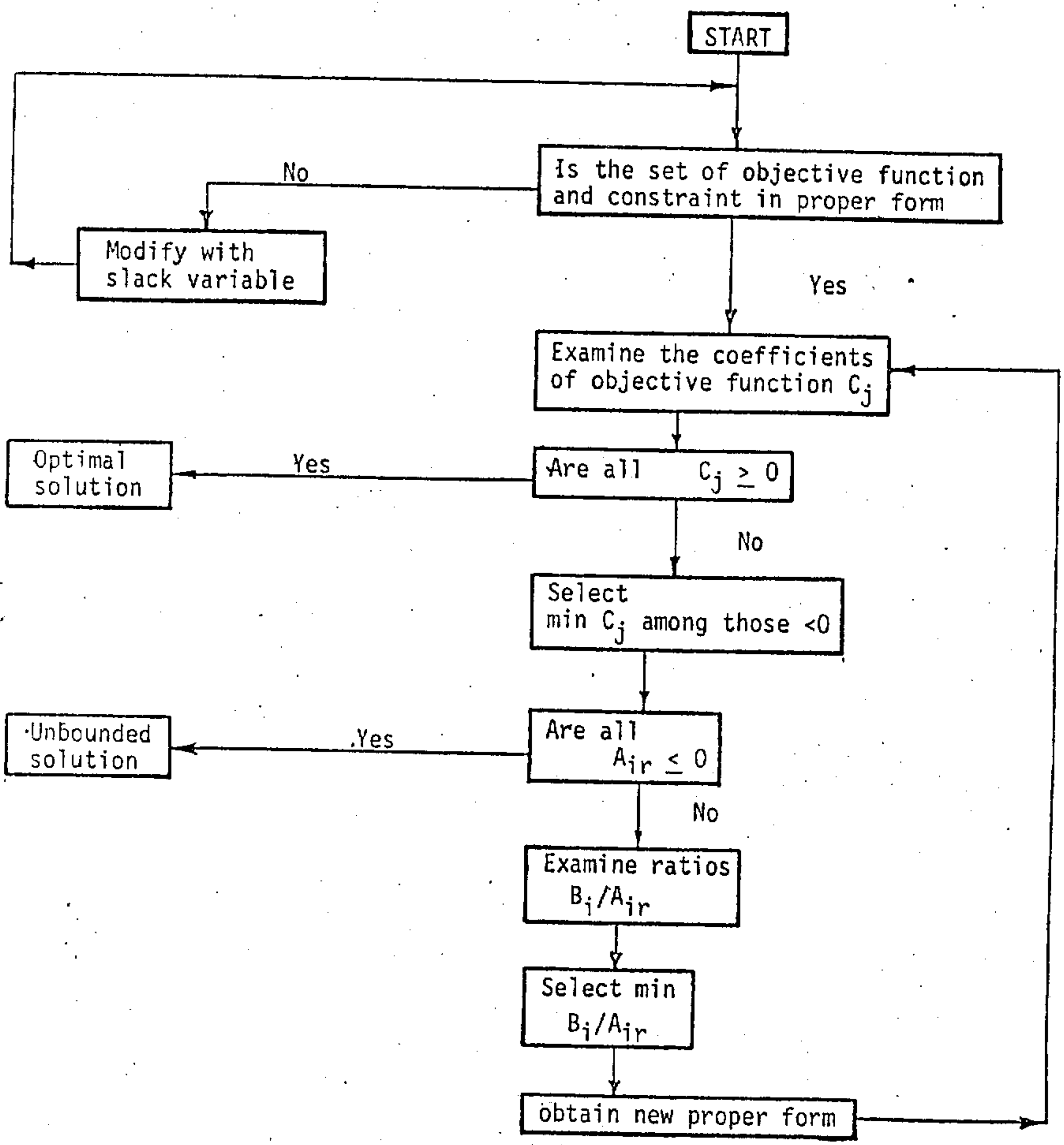
In order to illustrate the above Simplex procedure more clearly, a numerical example, given as an exercise in the standard textbook (53), is taken and solved in the following conventional way

$$\text{Max } Z = 3X_1 + X_2 + 2X_3$$

subjected to

$$X_1 - 2X_2 - X_3 \leq 10$$

FIGURE 1.. A flow chart showing the steps involved in simplex method of linear programming.



$$2X_1 + X_2 + 2X_3 \leq 12$$

$$X_1 - X_2 + X_3 \leq 5$$

$$X_1, X_2, X_3 \geq 0$$

Here our objective is to find out the values of X_1, X_2, X_3 in such a way that these values will satisfy constraints at the same time give maximum value of the objective function.

As all the given constraints are "less than" form, we can easily convert the above original problem into proper form (technically known as Canonical form) by minimizing the objective function and introducing slack variables X_4, X_5 and X_6. With such transformation we get,

$$\text{Minimize } -Z = -3X_1 - X_2 + 2X_3$$

subjected to

$$X_1 - 2X_2 - X_3 + X_4 = 10$$

$$2X_1 + X_2 + 2X_3 + X_5 = 12$$

$$X_1 - X_2 + X_3 + X_6 = 5$$

The rest of the steps are given in the following tabular form on the next page.

B_i		X_1	X_2	X_3	X_4	X_5	X_6	
				ORIGINAL FORM				
10		1	-2	-1	1	0	0	
12	A_{ij}	2	1	2	0	1	0	A_{ij}
5		1	-1	1	0	0	1	
$-Z = 0$	C_i	-3^*	-1	2	0	0	0	C_i
				FIRST ITERATION				
5		1	-1	-2	1	0	-1	
2	A'_{ij}	0	3	0	0	1	-2	A'_{ij}
5		1	-1	1	0	0	1	
$-Z=15$	C_i	0	-4^*	5	0	0	3	C_i
				SECOND ITERATION				
17/3		0	0	-2	1	1/3	5/3	
2/3	A'_{ij}	0	1	0	0	1/3	-2/3	A_i
17/3		1	0	1	0	1/3	1/3	
$-Z = 53/3$	C_i	0	0	5	0	4/3	1/3	C_i

As all coefficients of new objective function are positive, we hit the optimal solution and thus the above iteration procedure is stopped and the final row provides optimal solution as

$X_5 = 0 = X_6 = X_3$

$X_1 = 17/3$

$X_2 = 2/3$

$X_4 = 17/3$

Putting these values in objective function

$$Z\ Max = \frac{53}{3}$$

The nicity of this iterative procedure lies in the fact that it is general and thus can be applied to any discipline once formulation is completed by the expertises in the field. This procedure is flexible enough to include variation in the standard form and can be easily modified to suit changed conditions with the help of Dualily theory which is an important property of linear programming. Generally linear programming is applicable when

1. all mathematical functions are linear,
2. resource usage is directly proportional to the activity conducted individually,
3. optimal solution is a combination of integer and fractional values of variables, and
4. all of the coefficients in the linear programming model are known constants (53).

Integer Programming: Many times decision variables correspond to men or machines or vehicles participating in particular activity (53). In these situations, there is an automatic restriction imposed on decision variables to have only integar values. This case is solved by integar programming which is essentially the same as linear programming. One approach to solve integer programming problems is to consider it as a linear programming problem and then solution is obtained by conventional Simplex method. If the solution consists of integer values then that solution is an optimal solution. If not, then the original linear programming problem is modified by adding new constraints which eliminates some non-integer solutions (9). The whole procedure is repeated with new constraint until integar variables are found out as a final solution. However, the key step in this procedure is to determine the new constraint.

Parametric Linear Programming: This is also known as Sensitivity analysis in which the parameters are changed and their effect on objective function is observed. This technique provides valuable information about

1. Variables that have direct effect on optimal solution and
2. Evaluation of new variables or constraints

Quadratic Programming: This classification is applicable to cases where objective function is the sum of linear and quadratic terms and all constraints are linear. Mathematically, it is represented by

objective function:

$$Z = \sum_{j=1}^{n} C_j X_j + \sum_{j=1}^{n} \sum_{k=1}^{n} D_{jk} X_j X_k$$

subjected to

$$\sum_{j=1}^{n} A_{ij} X_j \leq B_i \quad \text{for } i = 1, 2, \ldots$$

and variables $X_j \geq 0$ for $j = 1, 2, \ldots$

where A_{ij}, B_i, C_j, D_{jk} are constants

The procedure for finding optimal solution consists of converting this nonlinear problem to linear form with the help of Kuhn-Tucker conditions and then solving linear programming problems with routine techniques described previously.

Lagrange's Undetermined Multiplier: This is one of the multivariate techniques used when objective function is nonlinear with all equality constraints as given below.

objective function: $Z = F(X_1, X_2, X_3 \ldots X_n)$

subject to

$$G_1(X_1, X_2, X_3, \ldots X_n) = B_1$$

$$G_2(X_1, X_2, X_3, \ldots X_n) = B_2$$

$$G_m(X_1, X_2, X_3, \ldots X_n) = B_m \qquad \text{(A)}$$

where all $X_j \geq 0$ and B_n are constants

F, G_1 G_2 $\ldots G_m$ are functional relationships

In order to solve the above model, the problem is expressed in the form of Lagrangian L which is defined as

$$\text{Max } L = F(X_1, X_2, X_3, \ldots X_n) + \sum_{L=1}^{m} \lambda_i [G_i(X_1, X_2, X_3 \ldots X_n) - B_i]$$

where $\lambda_i (i = 1, 2, 3 \ldots m)$ are Lagrangian multipliers and two necessary conditions for solution are

$$\frac{\partial L}{\partial X_j} = 0 \qquad \text{where } j = 1, 2 \ldots$$

and

$$\frac{\partial L}{\partial X_i} = 0 \qquad \text{where } i = 1, 2 \ldots$$

This leads to n+m equations for n-m unknowns and therefore the solution is obtained by solving n+m simultaneous equations.

<u>The Kuhn-Tucker Conditions:</u> Another similar type of solution for more generalized nonlinear formulation is obtained with the help of the Kuhn-Tucker conditions. These conditions for standard nonlinear form represented by equations (A) are

If $\overset{*}{X}_j > 0$ then

$$\frac{\partial f}{\partial X_j} - \sum_{i=1}^{m} \lambda_i \frac{\partial G_i}{\partial X_j} = 0$$

$$X_j = X_j^* \quad \text{for } j = 1, 2, \ldots n$$

If $\overset{*}{X}_j = 0$ then

$$\frac{\partial f}{\partial X_j} - \sum_{i=1}^{m} \lambda_i \frac{\partial G_i}{\partial X_i} \quad X_j = X_j^* \quad \text{for } j = 1, 2, 3, \ldots n$$

If $\lambda_i > 0$ then

$$G_i - (X_i^*, X_2^*, \ldots X_n^*) - B_i = 0$$

$$\text{for } i = 1, 2, 3, \ldots m$$

If $\lambda_i = 0$ then

$$G_i(X_1^*, X_2^*, X_3^* \ldots X_n^*) - B_1 \leq 0$$

$$X_j^* \geq 0 \qquad \text{for } j = 1, 2, \ldots n$$

$$\lambda_i \; 0 \qquad \text{for } i = 1, 2, \ldots m$$

where G_i and F are functions defined in the previous section.

Thus, the procedure consists of

1. developing matrix of constants and variables (known as Hessian Matrix),
2. writing and selecting appropriate Kuhn-Tucker conditions depending upon nature of Hessian matrix, and
3. arriving at particular optimum values of variables satisfying above conditions.

Many times it beomes difficult to get optimal solution directly from the Kuhn-Tucker conditions. However, this procedure does provide clues for searching optimal solution.

Geometric Programming: In engineering problems, many times a designer's immediate interest is to know the percentage of resources to be spent on a particular activity of the process or operation rather than optimum values of the process variables. In this situation, Geometric Programming is the obvious choice of selection (53). The objective function is written in compact form as

$$Z = \sum_{i=1}^{m} C_i \prod_{j=1}^{n} X_j^{A_{ij}}$$

where $\prod_{j=1}^{n} X_j$ represent $X_1 \cdot X_2 \cdot X_3 \ldots X_n$ product

and there are n variables and m terms in the equation, with C_i and A_{ij} as constants.

If we introduce optimal weights W_i as

$$W_i = \frac{1}{Z^*} \left[C_i \prod_{j=i}^{n} (X_j^*)^{A_{ij}}\right] \text{ for } i = 1, 2 \ldots m \qquad (A')$$

This leads to

$$\sum_{i=1}^{m} A_{ij} W_i = 0$$

and $\Sigma W_i = 1$

The pecularity of these two conditions is that they do not depend on the cost coefficients C_i. Therefore, the solution obtained from this set of equations provides the proportion of total optimum ($\overset{*}{Z}$) to be spent on different items of objective function. Once this proportion is calculated then optimum value is automatically estimated by

$$\overset{*}{Z} = \prod_{j=1}^{n} \left(\frac{C_i}{W_i}\right)^{W_i}$$

If one is also interested in knowing the optimal values of decision variables, he can put estimated values of $\overset{*}{Z}$ and W_i in equation (A') and get X_j^* by solving the equation (A').

This procedure becomes handy when the number of terms on the right hand side of the equal sign (the value of m) are equal to the number of independent variables (value of n). However, in other cases, it becomes difficult to solve many nonlinear simultaneous equations resulting from four or five degrees of freedom (i.e. when $m-n \geq 4$ or 5).

Dynamic Programming: It is a powerful mathematical tool to solve sequential decision problems. Any system, which can be broken down into many subsystems, is susceptible for Dynamic Programming approach. Another requirement is that each stage of the problem must have finite number of states associated with it. The decision that is made in previous stages can be utilized either in current or in any other stages. The important characteristic is that, for a given state and stage of the problem, the optimal sequence of decisions is independent of the decisions made in previous stages. Thus, essential steps in Dynamic Programming approach are as follows:

1. Divide a system into N-stage serial system.
2. Formulate recursive relationship between the stage variables.
3. Maximize or minimize recursive equation in question and optimum set of decision variables is estimated at a particular stage, and
4. These optimum variables are transformed to the next stage and optimization techniques is again applied to combined system and final decision variables are determined (9,20,53).

Search Technique: This technique is unique in the sense that the previous techniques aim at mathematical solutions to decide optimum, whereas this technique directly searches for optimum by combining and varying variables in appropriate fashion. If the variables are changed in systematic fashion (with equal increments) then it is called Systematic Sampling Search. If only one variable is allowed to vary, then it is called Univariate search scheme. Thus, depending upon the way in which the search is made, there are many techniques available, such as Simultaneous search, Sequential search, Dichotomous search, Fibonacci search, Golden section search, Lattice search and finally Multivariate gradient search plans (9). The nicity of the Search Technique is that it is very general and can be applied to the problems which cannot be normally solved by other analytical techniques.

Simulation: This appears to be the most powerful and popular analytical tool available to water planners. It is basically a digital computer simulation in which characteristics of the system (in the form of functional relationships) are used to assess the response of selected output variables to the input variables. Simulation does not directly yield information such as the optimal capacity of a reservoir, instead, the output from a simulation model is used to construct a response surface which can be examined to determine an optimal solution as indicated by maximum and minimum points of the quantities of interest (9). Since simulation generally requires less number of assumptions than analytical models, there is increasing trend to first use an approximate analytical model to define the region of near optimality and then coverage to the optimal solution through simulation. The simulation model consists of a lengthy system description, a computer write-up, and finally computer output data. It has been a practice in the past to apply this technique to only multipurpose reservoir. However, recently it is being extensively used in the planning stage also.

Since the scope of this report is limited to the modeling of the Kissimmee River and Lake Okeechobee system, in light of these models and programming techniques, an effort is made in the following section to explore the various interdisciplinary modeling attempts reported so far in this direction.

INTERDISCIPLINARY MODELING EFFORTS FOR KISSIMMEE RIVER AND LAKE OKEECHOBEE SYSTEM

From the discussion of the previous section it is clear that a water system can be analyzed through different perspectives. Such is indeed a case for the Kissimmee River and Lake Okeechobee water system. For such a system, efforts are being made to look at

1. quality aspect,
2. hydrologic characteristics
3. ecological interactions and
4. social, economic and technological considerations

Department of Pollution Control (DPC) of the State of Florida is currently investigating the pollutional aspect of the Kissimmee River. Connell Associates, consultant to the DPC, are expected to analyze the dissolved oxygen levels in the Kissimmee River with one dimensional water quality model suggested by O'Conner (54). The final goal of their study is basically to propose the degree of removal at different point sources to maintain the desirable dissolved oxygen levels in the Kissimmee River taking into account the major, physical, chemical and biological interactions (55). Simultaneously a group at the University of

Miami is working on the water quality model study of the Kissimmee River basin. In this study, an effort is being made to develop models to combine hydrology and water quality aspects. The final outcome of his study is expected to supplement a comprehensive model which can hopefully relate hydraulic loading and environmental perturbations (29).

Another research group, headed by Professor Odum at the University of Florida, is involved in studies related to the potential eutrophication in Lake Okeechobee. Their line of approach would consider properties of nutrient, oxygen levels, deposition of bottom sediment, color, turbidity and various ecological interactions between benthic plants, marshes and microbial life in water. Such information would then subsequently be fed in dynamic analog models to simulate and predict the effects of various environmental factors on the eutrophication in Lake Okeechobee (41).

An operational watershed model based on hydraulic characteristics of the Kissimmee River basin was developed by Sinha, L. K. (52). In this hydraulic model, the water surface elevations are successfully simulated for different structures of the Kissimmee River and provided the operational information regarding water release, head water elevation and tailwater elevation at these control structures. The merits of such operational watershed models are discussed in detail by Lindahl and Hamrick (32).

A hydrology model is also developed for the Taylor Creek which is draining into Lake Okeechobee. As mentioned earlier, in this approach, Lindahl has simulated streamflow (quantity model) of Taylor Creek by computing infiltration, water loss, recovery and time distribution of water at the watershed outlet (50, 51). The various formulations and discussions involved in developing these hydrology models are available in many recent publications (8, 32, 50, 51, 52).

While developing these procedures only through one specialized perspective alone (like hydrology, or ecology, or water quality etc.) it is realized that there are many conflicting interests associated with water systems such as Kissimmee River and Lake Okeechobee. To include these factors effectively in setting the planning guidelines, two studies viewed water systems from social, economic and institutional standpoint also. In an effort to develop an optimum water allocation model for the Kissimmee River basin, Reynolds, Conner Gibbs and Kiker of the University of Florida have used linear programming and simulation techniques to evaluate various policy alternatives with respect to the hydrologic, economic and institutional aspect of the water system in question (46). In this methodology, hydrologic and economic data are first collected and recreational use of water over the four subregions of the Kissimmee River is formulated. With these inputs, a linear programming water allocation model is set up and solved. In addition to the optimum values of the water allocations to different uses, this model is shown to be capable of indicating the relative sensitivity of the various hydrologic and economic factors of the system (46). Similarly, a simulation model of the water management system of the Kissimmee River is designed to develop policy statements regarding temporal and spatial water storage, consumptive withdrawals, minimum outflows, land and water use patterns.

Recently, the Heaney and Huber group at the University of Florida has completed the environmental resources management studies of the Kissimmee River basin. Although the basic objective of optimum resource allocation is similar to the previous study, the framework of analysis seems to be different. In initial stages environmental inventory with an economic and hydrologic assessment of physical and land system alternatives for the Kissimmee River basin is performed and then subsequently the tasks of environmental planning and simulation are completed to include social, ecological and water quality considerations (24).

Certain techniques applied to the analysis of the upper St. Johns River basin are tried for the Kissimmee River basin also.

After knowing the different kinds of available models in general and modeling efforts for the Kissimmee River and Lake Okeechobee in particular, the immediate questions to be asked are?

1. How effective are these modeling procedures?
2. Is it possible to assess their adequacies?
3. Is there any other better way to these modeling efforts for our water systems in question?

The discussion in the next section is geared to provide some answers in that direction.

ADEQUACY OF THESE MODELING EFFORTS FOR KISSIMMEE RIVER AND LAKE OKEECHOBEE SYSTEM

It is conceivable that the success of the above mentioned modeling efforts is largely geared to the

1. sample size or data base,
2. the available computer capacity,
3. the validity of the assumptions and other simplifications,
4. estimation of the rate coefficients or the numbers that are arbitrarily chosen based on the value judgment and
5. verification procedure for the outcome.

In light of these factors, it seems that the studies undertaken for analyzing the Kissimmee River basin are well rounded from the scientific methodology standpoint, although not complete in all respects. In other words, the Kissimmee River basin is being studies through hydrology, hydraulics, water quality, economics, environment, social and institutional considerations, but political and ecological aspects for example, are not well formulated so far. For Lake Okeechobee on the other hand, it seems that the progress of developing interdisciplinary models is slow although effors are currently in progress in this direction.

As given in the program document and related publications, the main goal of the Central and Southern Florida Flood Control District in carrying out the Kissimmee River and Lake Okeechobee studies is "to determine the available water resource that will sustain in the way of population levels, associated land use and environmental factors together with various options for developing the total water resource" (1,43).

Before tieing together the outcome of these efforts with our prescribed goals, it seems essential to examine the methodologies involved in these efforts in light of the above factors.

First, although the data base for Kissimmee River and Lake Okeechobee may not be very huge, adequate data is collected by measurements or can be obtained by sending a questionaire independently in each effort. Second, such data are analyzed in cooperation with state agencies and universities. Therefore, enough computer capacity seems to be available in joint modeling efforts. Third, since the general methodology of model building involves invariably with the analytical solution of one kind or the other, many assumptions and simplifications are made. Although these approximations can be considered as restrictions on the system, these are generally decided either on the sound physical intuition or on the practical observations and thus, can be adequately checked. Similarly, the estimation of the rate coefficients and the subjective weights assigned in these modeling efforts may be questionable. However, the risk involved is not adequately estimating these coefficients can be reduced by an appropriate sensitivity analysis. Among five factors mentioned previously, it seems that the major limitation of these efforts is in the area of verification procedure. Although a completed study on the Kissimmee River basin is based on very detailed cost optimization analysis of various economic and environmental factors, the allocation or land use planning policies recommended in such studies are difficult to be verified. In other words, it may be possible that a change in the set of numbers may swing the conclusions the other way around. Based on this discussion, it can be summarized that although the current modeling methods are capable of including complexities, unfortunately there is no direct procedure to check the planning guidelines recommended by such detailed analysis. With a view to eliminate this limitation, it appears that the statistical models may be more useful for the Kissimmee River and Lake Okeechobee system as short term models. The required procedure available for the data base and the merits of these proposed models for our study areas follows.

DISCUSSION OF PROPOSED STATISTICAL MODELS

The prerequisite for the detailed planning analysis of water resources system is to formulate the interrelations between various system parameters. To achieve this objective statistical models are generally recommended. Therefore, statistical models are suggested for unfolding the functional relationships for Kissimmee River and Lake Okeechobee system.

Procedure of the Proposed Methodology:

As a first step, various physical, chemical, and biological water quality parameters coupled with all other interdisciplinary factors are identified for the Kissimmee River and Lake Okeechobee system.

Efforts then would be made to gather the data from various governmental or private organizations or from publications. If essential, and if it fits into the time framework, a questionaire can be sent to aquire the critical data.

In the next step, various statistical methods like stewise multiple regression, principal component analysis and multivariate analysis can be used to develop the required systems interrelationships.

The Available Data Base:

As a result of monitoring efforts of the U.S.G.S. and the F.C.D, the quarterly data for physical, chemical, biological parameters are available for the years 1970-71-72 and monthly values of similar parameters are obtained for the period of October 1972 to the present (26). It also appears that the hydraulic and hydrologic data can be obtained for the same time period. Thus, it seems possible to obtain two data sets of data, one data set with 42 sample points for Lake Okeechobee and the other data sets with 52 data points for Kissimmee River. It is to be noted here that these total data points are based on the information available from the U.S.G.S. or F.C.D. alone. It is possible to increase this number of data points if other local and regional agencies have monitored the above water systems at different time frameworks. In other words, these sample points represent a minimum available data base for the proposed analysis.

Merits of the Proposed Methodology:

Although modern water resources analysis is invariably coupled with statistical analyses of various types, there exist extreme opinions about its capability in setting planning guidelines. Some optimistic water engineers do not hesitate to say that "they can prove anything with statistics". Whereas, a few pessimistic professionals think that "one cannot prove anything by statistics". The author, however, supports a general feeling of the scientific community that if the rules of statistics are understood and properly applied, statistics neither lie nor mislead. As a matter of fact, according to the eminent meteorologist Dr. Louis J. Battan, statistics is considered as the only satisfactory means available for disproving something (2,47). This is indeed true in planning areas where decisions are made on the basis of variable output obtained as a result of numerous and complex environmental interactions. Primarily, with this thinking the statistical models are suggested in modeling efforts of the Kissimmee River and Lake Okeechobee.

It may be argued that the twenty-five data points may not be adequate to perform sophisticated statistical analysis. However, for statistical regression analysis, it seems that currently available data base can estimate the nonlinear regression coefficient and compute multiple regression coefficients on the first trial basis. Although more data points would increase the confidence in estimating these key coefficients, it is to be realized that the set of available values is the only source of information from which regression equations can be developed unless some special efforts are made to collect data by sending questionaires. Under this data constraint, the proposed statistical methods seems to supercede the other technqiues. When more data are available in the future, then these can easily be modified.

With recent advancements in the regression analyses, it is also possible to include different types of variables (such as arithmetic, logrithm and binary) into the regression equations (5,6). In this way, it may be possible to include in the binary form certain qualitative factors of the areas in the final formulation.

Another added advantage of these statistical models is that these models can easily incorporate quality and quantity aspects into a one combined equation. This is not so easily and clearly possible with the traditional approach of solving corresponding combined differential equations.

It is indeed true that the proposed statistical models will develop the relationships that are valid only for specific regions like the Kissimmee River and Lake Okeechobee. However, it is very clear that the modeling efforts of the FCD is directed on the regional basis and not on a continental basis any way. Thus, the specific nature of these statistical models is intentional and is not considered as a limitation.

Last, but not least, is that these statistical models are especially useful for the Lake Okeechobee system in which no substantial modeling effort is reported. Under these circumstances, the outcome of these statistical models would yield valuable information about the chemical, biological and physical interactions which in turn can be used in subsequent simulation and sensitivity analysis.

CONCLUSIONS:

Based on the preceding discussion of the different types of modeling procedure, the following conclusions of a general type can be drawn at the starting stage of the Kissimmee River and Lake Okeechobee study:

1. It appears that the past modeling efforts are more concentrated on the Kissimmee River system rather than on the Lake Okeechobee system. The modeling of the lake is still in the developing stage because of the following:

   a. inadequate understanding of geochemical interactions coupled with dilution, biological and circulation patterns.

   b. its complex nature of beneficial uses and

   c. irregular behavioral pattern of nutrient recycling coupled with various unknown pathways of sources and sinks.

2. In addition to the currently in progress methodologies, statistical methods seem to provide useful supplementary interrelationships which can be used in the simulation procedure.of the other proposed modeling efforts.

3. With the current cooperative efforts of the Department of Administration Department of Pollution Control, University of Miami, University of Florida, Central and Southern Florida Flood Control District and many other enterprises,it seems possible in the near future to broaden the understanding of the interactions of the Kissimmee River and Lake Okeechobee system to the extent that it can be used in setting the planning guidelines by exploring social, economic, legal, political and environmental aspects of these water systems.

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